Accelerated Life Testing of PV Arc-Fault Detectors

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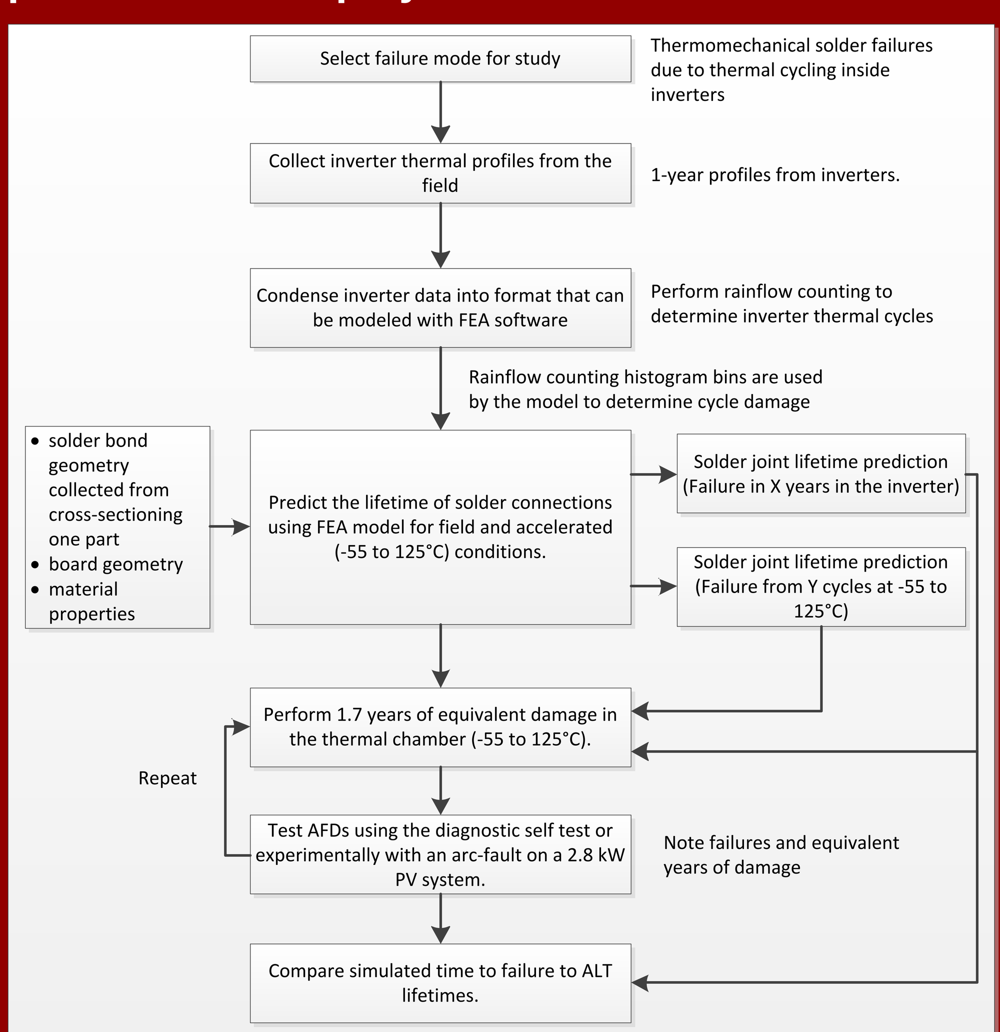
As of 2011, the *National Electrical Code®* (*NEC*) has required arc-fault circuit interrupters (AFCIs) to be incorporated into photovoltaic (PV) systems to prevent fires. Some manufacturers are designing AFCIs to consist of arc-fault detectors (AFD) incorporated into inverters or combiner boxes in order to take advantage of the DC switching functionality of the existing hardware. Since AFCIs and AFDs are safety devices, it is critical to ensure the long-term functionality of AFD devices in these harsh environments. Sandia National Laboratories (SNL) has performed accelerated life tests on 10 AFDs. The devices were tested after being subjected to the thermal damage equivalent of 1.7-year increments in an inverter until 77.6 equivalent years of solder fatigue damage. 30% of the boards experienced component failures but there were no solder failures, indicating solder fatigue is not the primary failure mode. Based on these results, Sandia recommends an appropriate burn-in process for production of arc-fault devices.

Solder Accelerated Life Testing Process

While the primary failure mode for AFD devices is unknown, microelectronic and discrete component solder bonds are known to fail on printed wiring boards as a result of harsh thermal environments. Specifically, thermo-mechanical solder fatigue failure is common in thermal cycling environments (e.g., automotive applications), so it was believed solder fatigue would be one of the leading causes of AFD failure in outdoor inverters which experience diurnal and seasonal cycling. To determine the lifetime of the solder joints, the following process was employed:

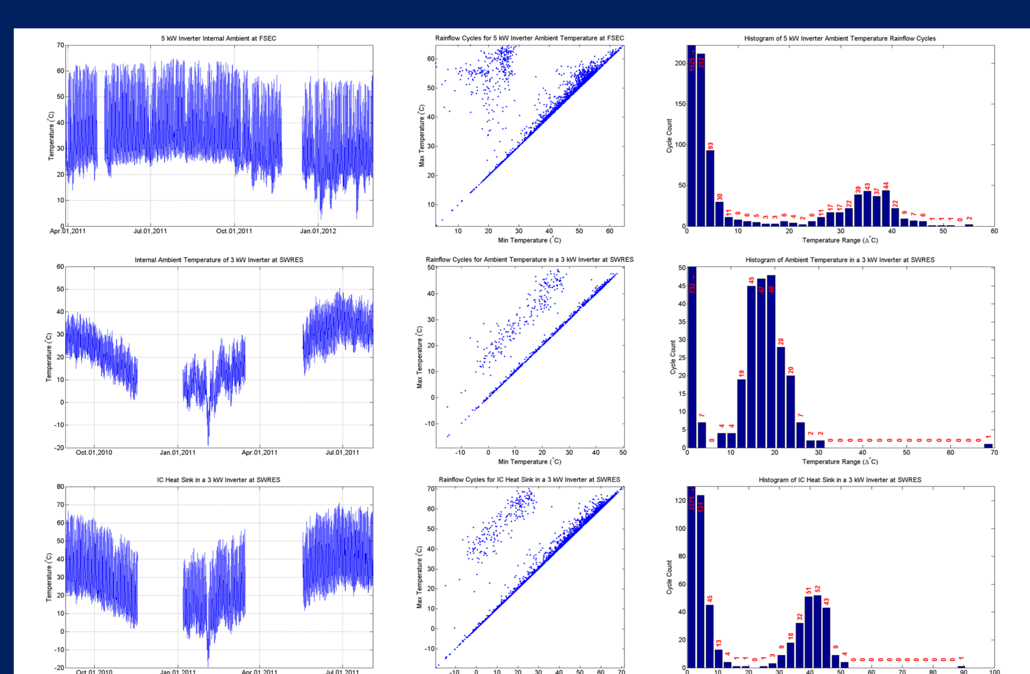


Process for determining the equivalent lifetime of the arc-fault detectors for the solder fatigue failure mode.

Modeling the Thermal Environment of an Inverter

To find the number of accelerated thermal cycles which produce 1-year of equivalent inverter exposure, a SNL-developed finite element analysis (FEA) code with Unified Creep Plasticity Damage (UCPD) material models for solder was run for rainflow count binned inverter thermal profiles and compared to simulations of -55 to 125°C cycles. The number of equivalent accelerated cycles was determined for the following thermal histories:

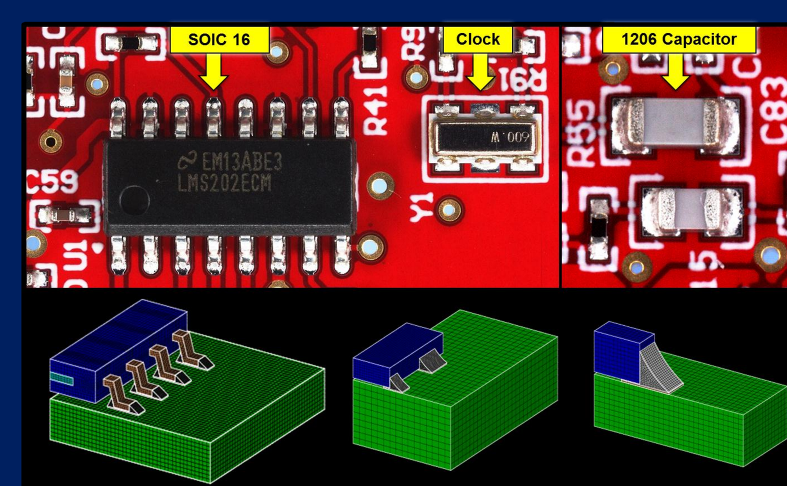
1. ambient temperature within a 5 kW inverter at the Florida Solar Energy Center (FSEC)
2. ambient temperature within a 3 kW inverter at the Southwest Region Experiment Station (SWRES) at the New Mexico State University in Las Cruces, NM.
3. integrated circuit heat sink temperature within a 3 kW inverter at SWRES (theoretical comparison only).



Thermal histories of three locations in PV inverters, associated rainflow matrices, and resulting histograms of rainflow counts.

Solder Joint Failure Analysis

Solder fatigue damage calculations for the joints of the gull-wing 16-lead small outline integrated circuit (SOIC), 6-joint leaded ceramic chip carrier (LCCC) clock, and 1206 capacitor were performed.



Calculations indicated that the fatigue damage rate was highest in the clock solder joints. The FSEC ambient inverter thermal history was the most damaging internal ambient environment, so it was used to find the expected life and equivalent number of accelerated life cycles.

		Crack Initiation Failure Criterion			50% Solder Crack Failure Criterion			Complete Crack (Open) Failure Criterion		
Bin (ΔT)	*Count*	*Damage per cycle*	*Damage per history*	*Damage per year*	*Damage per cycle*	*Damage per history*	*Damage per year*	*Damage per cycle*	*Damage per history*	*Damage per year*
4.482	335	5.52E-12%	1.85E-09%	2.19E-09%	2.08E-13%	6.98E-11%	8.28E-11%	1.04E-13%	3.49E-11%	4.14E-11%
10.580	25	2.10E-06%	0.00005%	0.00006%	1.04E-07%	2.60E-06%	3.09E-06%	5.21E-08%	1.30E-06%	1.55E-06%
16.086	11	0.00005%	0.00056%	0.00066%	4.65E-06%	0.00005%	0.00006%	2.15E-06%	0.00002%	0.00003%
21.282	12	0.00028%	0.00337%	0.00400%	0.00003%	0.00036%	0.00043%	0.00001%	0.00016%	0.00020%
27.953	34	0.00088%	0.03002%	0.03561%	0.00011%	0.00389%	0.00461%	0.00005%	0.00177%	0.00210%
33.350	78	0.00216%	0.16811%	0.19942%	0.00028%	0.02167%	0.02572%	0.00013%	0.01016%	0.01206%
38.323	124	0.00438%	0.54338%	0.64457%	0.00062%	0.07654%	0.09086%	0.00026%	0.03280%	0.03894%
43.061	38	0.00811%	0.30807%	0.36544%	0.00115%	0.04368%	0.05185%	0.00047%	0.01784%	0.02118%
48.113	8	0.01393%	0.11147%	0.13223%	0.00185%	0.01481%	0.01759%	0.00074%	0.00588%	0.00698%
55.334	3	0.02258%	0.06773%	0.08035%	0.00278%	0.00833%	0.00989%	0.00106%	0.00319%	0.00379%
Total	668	0.05237%	1.23277%	1.46233%	0.00682%	0.16934%	0.20101%	0.00273%	0.07183%	0.08527%
Years to Failure in Field		68.4			497.5			1173		
Damage per -55 to 125°C Cycle		1.1700%			0.13333%			0.02941%		
Accelerated Cycles to Failure		85.5			750			3400		
Accelerated Cycles per 1 Year in Field		1.25			1.51			2.90		

Damage from rainflow cycle bins and calculations for equivalent damage from accelerated cycles for three crack-propagation failure criteria.

Results and Discussion

All 10 of the AFD boards were exposed to 225 thermal cycles. After every five cycles, the boards were tested using the internal diagnostic self test function; and after 45 cycles (15.5 years of equivalent solder damage using the 100% solder crack failure criteria), physical arc-fault tests were conducted at the Distributed Energy Technologies Laboratory at SNL. After all the accelerated cycles, there were no failures from solder fatigue. Rather, there were infant mortality failures of 30% of the AFDs; and therefore, the expected lifetimes of those parts could not be calculated using the FEA model. In all the failed boards, visual inspection of the solder joints was performed and all joints were in excellent condition.

Thermal Cycles

AFD Number	0 DST	0 AFT	5 DST	10 DST	15 DST	20 DST	25 DST	30 DST	35 DST	40 DST	45 DST	45 AFT
1	P	P	P	P	P	P	P	P	P	P	P	P
2	P	P	P	P	P	P	P	P	P	P	P	P
3	P	P	P	P	P	P	P	P	P	P	P	P
4	P	P	P	P	P	P	P	P	P	P	P	P
5	P	P	F									F
6	P	P	P	P	P	P	P	P	F			F
7	P	P	P	P	P	P	P	P	P	P	P	P
8	P	P	P	F								F
9	P	P	P	P	P	P	P	P	P	P	P	P
10	P	P	P	P	P	P	P	P	P	P	P	P
Open Failure Criterion (years)	0.0		1.7	3.4	5.2	6.9	8.6	10.3	12.1	13.8	15.5	

AFD Number	50 DST	55 DST	60 DST	65 DST	70 DST	75 DST	80 DST	85 DST	90 DST	90 AFT	95 DST	100 DST	105 DST	110 DST	115 DST	120 DST	125 DST	130 DST	135 DST	135 AFT
1	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
2	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
3	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
4	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
5																				
6																				
7	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
8																				
9	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
10	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Open Failure Criterion (years)	17.2	19.0	20.7	22.4	24.1	25.9	27.6	29.3	31.0		32.8	34.5	36.2	37.9	39.7	41.4	43.1	44.8	46.6	

Thermal Cycles

AFD Number	140 DST	145 DST	150 DST	155 DST	160 DST	165 DST	170 DST	175 DST	180 DST	180 AFT	185 DST	190 DST	195 DST	200 DST	205 DST	210 DST	215 DST	220 DST	225 DST	225 AFT	Cycles to Failure	Years to Failure
1	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
2	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
3	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
4	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
5																					5	N/A
6																					35	N/A
7	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
8																					10	N/A
9	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
10	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
Open Failure Criterion (years)	48.3	50.0	51.7	53.4	55.2	56.9	58.6	60.3	62.1		63.8	65.5	67.2	69.0	70.7	72.4	74.1	75.9	77.6			

Summary of the AFD board tests. The equivalent number of years to failure in the field could not be calculated because the thermalcycles did not accelerated the solder fatigue failure mode.

Conclusions:

1. The on-board diagnostic self test function of the AFDs works well to indicate when the functionality of the boards is lost.
2. Solder fatigue is an unlikely AFD failure mode when installed in an inverter.
3. Since the AFD are required to operate for long periods of time in harsh environments, using a burn-in (stress screen) process to identify faulty components will be used in the future.

NNSA National Nuclear Security Administration

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